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Spatial and temporal distribution of NO_2 and SO_2 in Inner Mongolia urban agglomeration obtained from satellite remote sensing and ground observations

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ABSTRACT

Nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) are important pollution gases which can affect air quality, human health and even climate change. Based on the combination of tropospheric NO_2 and SO_2 column density products derived from OMI satellite with the ground station observations, this study analyzed the spatial-temporal distribution of NO_2 and SO_2 amount in Inner Mongolia urban agglomerations. It shows that NO_2 increased continually from 2005 to 2011 at a rate of 14.3% per year and then decreased from 2011 to 2016 at a rate of −8.1% per year. SO_2 increased from 2005 to 2007 with a rate 9.7% per year. While with a peak value in 2011, SO_2 generally showed a decreasing trend of −1.6% per year from 2007 to 2016. With regard to the spatial pattern, the highest levels of NO_2 occur in Hohhot and Baotou, followed by Wuhai and Ordos, the least in Bayannur. Compared with NO_2, the spatial distribution of SO_2 is slightly different. The pollution of SO_2 is the most serious in Wuhai, followed by Hohhot and Baotou, and the lightest in Ordos and Bayannur. The diurnal variations of NO_2 and SO_2 are basically the same, which decrease from 0:00 to 6:00, then increase to a peak value at 8:00, and decrease from 8:00 to 15:00. The diurnal variation of NO_2 and SO_2 is highly related to the diurnal variation of both anthropogenic emission and boundary layer height. Differently, the long-term spatial-temporal distribution of NO_2 and SO_2 are more closely related to human activities.

1. Introduction

In the past decades, coupled with China's burgeoning economy is the terrible air pollution (Chan and Yao, 2008), which is mainly caused by China's industrial explosive growth and urbanization development. Air pollutants can be divided into two forms, particulate matter (PM) and gaseous pollutants. PM has attracted great public concern because of its severe health impact (Yuan et al., 2012; Chang, 2012), especially for cardiovascular and respiratory disease, as well as reduced visibility caused by smog. Gaseous pollutants, such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and ozone (O_3), also play very important roles in our atmospheric environment and get more and more attentions (Hao et al., 2007; Wang et al., 2012).

NO_2 and SO_2 are both important trace gases and play a significant role in the complex atmospheric chemistry process of the troposphere, causing a series of urban environmental pollution problems such as acid rain, haze and photochemical smog (WHO, 2000; IPCC, 2007; He et al., 2007; Shon et al., 2011). The secondary sulfate and nitrate particulate is formed by oxidation of gas granules, contributing to the particle concentration in the air and thus influencing the radiative budget and climate (Kajino et al., 2011). They can also promote the formation of acid rain and cause the decrease of crop yields and destruction of ecology (Richter et al., 2006; Dickerson et al., 2007). NO_2 is primarily released by anthropogenic emissions, which contain the industrial burning of fossil fuels such as coal, oil and gas, vehicle exhaust, biomass burning, and electricity generation. In terms of natural sources, it is

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emitted from soils through the decomposition process of nitrates and can also be produced by lightning (Richter and Burrows, 2002; Cheng et al., 2012). Similarly, SO_2 is released into the atmosphere through both natural and anthropogenic emissions. Natural sources mainly refer to volcanic eruptions while anthropogenic sources include the burning of fossil fuels containing sulfur for domestic heating and the power generation for industrial activities (Zhang et al., 2017).

Over the years, researchers began to realize the detrimental effects of NO_2 and SO_2 to human health and plants, thus carried out studies about these two polluted gases (Ul-Haq et al., 2015). Compared with traditional ground station measurements which can provide continuous observations of near surface pollutants for a long time, satellite remote sensing offers other advantages, such as a coverage of large area with high spatial continuity. The satellite observations allow us to study the long-term spatio-temporal distribution of NO_2 and SO_2, the characteristics of long-distance transport (Zhang et al., 2008), as well as the pollutant contribution from various sources (Wang et al., 2012; Lu et al., 2013). To effectively acquire information of atmospheric pollutants, a lot of on-board satellite instruments are designed, such as Global Ozone Monitoring Experiment (GOME), SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY), GOME-2 and Ozone Monitoring Instrument (OMI). OMI is widely used and has high spatial and temporal resolution (Krotkov et al., 2016; Levelt et al., 2018). As overviewed by Levelt et al. (2018), OMI has been applied to various study themes including air quality monitoring, detection of ozone, volcanoes, spectral solar radiation, and so on. For air quality monitoring, OMI can provide information of several key pollutants such as NO_2, SO_2, aerosols, and HCHO. Damiani et al. (2012) used the ground-based total ozone measurements from 2007 to 2009 in the Arctic to check the quality of OMI, GOME and SCIAMACHY satellite-based data, and found that there was a good agreement between satellite- and ground-based observations despite of some systematic biases. Ul-Haq et al. (2015) investigated temporal trends, seasonality, and anomalies of tropospheric NO_2 pollution over four basins in South Asia using OMI measurements during the period 2004–2015. Lamsal et al. (2015) quantified the NO_2 temporal trend from 2005 to 2013 over the United States using surface measurements and tropospheric NO_2 vertical column density (VCD) data from OMI products. Krotkov et al. (2016) expanded the study area and used the OMI observation to investigate the SO_2 and NO_2 pollution changes over different countries of the world for the period of 2005–2014.

There are also many studies regarding the OMI-observed SO_2 and NO_x emission trends over China (van der A et al., 2017; Liu et al., 2016, 2017; Cui et al., 2016; Li et al., 2010, 2017; Zhang et al., 2017). Li et al. (2010) found the large reduction of SO_2 emissions from Chinese power plants in 2005–2007 based on OMI observations, and Li et al. (2017) indicated that SO_2 emission have declined by 75% in China since 2007 using OMI observations, making China surpassed by India for the total anthropogenic SO_2 emissions. Liu et al. (2016) investigated the temporal variation of NO_x over China at a national level based on both OMI observations and emission inventories, and they found a deceasing trend of column NO_2 by 32% from 2011 to 2015. Liu et al. (2017) further investigated the NO_x emissions from 48 cities and seven power plants over China, and found an increase by 52% from 2005 to 2011 and a decrease by 21% from 2011 and 2015 based on OMI observations. van der A et al. (2017) studied the air quality trends from 2005 to 2015 and evaluated the effectiveness of air quality policy for SO_2 and NO_x emissions in China. Zhang et al. (2017) analyzed the long-term trend of spatial and temporal distribution of NO_2 and SO_2 column density in Henan Province using OMI product. Cui et al. (2016) indicated that western China experienced rapid growth of NO_2 during 2005–2013, including the Inner Mongolia city cluster region. Note that Cui et al. (2016) mainly focused on regional statistical study of NO_2 from 2005 to 2013 for several regions in western China. By contrast, there is no intensive study for the gaseous pollution of SO_2 and NO_2 with high city/county level resolution over the Inner Mongolia region so far.

Inner Mongolia accounts for 12.3% of the land area in China and is rich in natural resources, of which coal reserves rank the second place among thirty-four provinces in China, making it become China's important energy heavy chemical base (NBS, 2013). Industries such as thermal power, chemical engineering and metallurgy impose a heavy burden on air quality. Various types of air pollutants have been increasing in recent years. Particularly, the amount of coal burning has increased greatly in winter heating period, making the air quality worse. As indicated by Cui et al. (2016), the increasing trend rate of NO_2 in 2005–2013 is as high as 10.2 ± 1.3% per year for the Inner Mongolia region. Currently, the first pollution-contributing factor is particulate matter, which is mainly from natural coal ash emission, dust and automobile exhaust emissions; and the second is SO_2 (IMESB, 2006). How to make a balance between the energy structure modulation and the improvement of air quality is an essential issue for public interests. To do that, we first need to obtain detailed pollution status over this region, such as SO_2 and NO_2. Therefore, this study aims to investigate the long-term trend and spatial distribution characteristics of NO_2 and SO_2 in Inner Mongolia urban agglomerations using both OMI measurements and ground-station observations.

The paper is organized as follows. Section 2 describes the data and method. Section 3 analyzes the spatial-temporal trends of NO_2 and SO_2 at cities in Inner Mongolia, and section 4 summarizes the findings.

2. Data and method

2.1. Study region

Inner Mongolia is the third largest province in China, with an area of about 1,183,000 km^2, population of 25 million, and Gross Domestic Product (GDP) of 1.78 trillion RenMinBi (RMB) in 2015 (CSY, 2015). From 2006 to 2011, the GDP growth rate was between 15% and 20% (generally ~15%) per year while it is about 7% after 2011 because of the adjustment of economic policy.

The study region is located in the core area of the middle and western Inner Mongolia, including Hohhut, Baotou, Ordos, Bayannur and Wuhai. Relying on abundant coal and natural gas resources, Hohhut-Baotou-Ordos (H-B-O) agglomeration has become the most dynamic economic circle in Inner Mongolia autonomous region. Hohhut is the capital city; Baotou is the largest city of Inner Mongolia; and Ordos is an emerging prairie city with rich energy resources. As shown in Fig. 1, Hohhut, Baotou and Ordos are situated in the Hetao plain with Yinshan mountain on the northern area, whereas Bayannur and Wuhai are in the ordos plateau. The difference of topography may influence the transport of air pollutants. In this study, we assume that natural contribution is roughly uniform in space (cities) and time while some uncertainties could be introduced. Generally, the anthropogenic

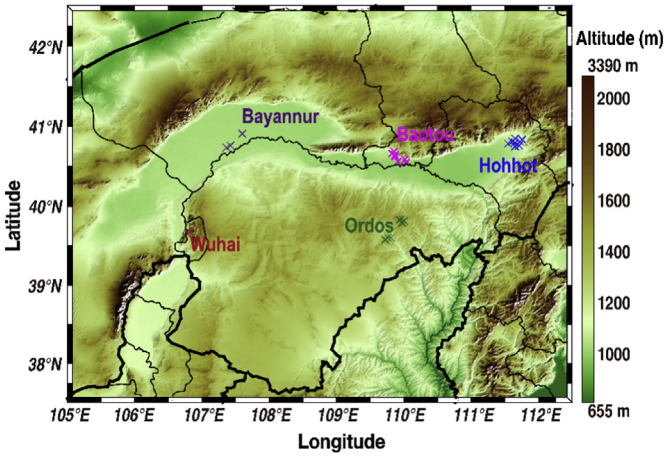

Fig. 1. Topographic map and the site distribution of Inner Mongolia urban.

emissions of NO_2 and SO_2 are much larger than natural contributions in these cities. By investigating the spatio-temporal distribution of NO_2 and SO_2 in these representative cities, we can evaluate the influence of human activities on the air quality of Inner Mongolia during past few years.

2.2. Aura satellite and OMI

Aura is a sun-synchronous orbit satellite tracking at 705 km altitude and crossing the equator at about 13:45 local time (LT), which was launched on July 15, 2004 (OMI Data User's Guide, 2012). It aims for observations and studies of the air quality, the ozone layer of earth, and climate change. OMI is a nadir pointing hyper-spectral imaging sensor aboard Aura spacecraft with a spatial resolution of 13 km × 24 km. It covers the whole earth once a day and provides the measurements of ozone profile, NO_2, SO_2, aerosol, cloud, as well as the trace gases such as HCHO, BrO and OClO.

Both Level 2 and daily Level 3 product of the planetary boundary layer (PBL) SO_2 and tropospheric NO_2 vertical column density (VCD) data were employed in this study. The VCD is defined as the amount of molecules for a specific atmospheric gas from the surface to the height indicated, such as the instrument height (Lamsal et al., 2015). The Level 2 (orbital swaths) product has individual files for each orbit of data at a spatial resolution of 13 kmx24 km, while the Level 3 product is a gridded data on uniform space-time scales with a 0.25° × 0.25° spatial resolution and daily time resolution (Eskes and Boersma, 2003; Boersma et al., 2011). The Level 2 product provides instantaneous NO_2 and SO_2 data which can be used to match the surface site hourly observations, while the Level 3 product are processed daily gridded data, which is more suitable for long-term trend analysis. Therefore, in this study, the former is used for the comparison with the ground-based observations and the latter is applied to the analysis of spatial distribution and long-term spatial-temporal trend of NO_2 and SO_2 over the Inter-Mongolia region.

2.3. Ground station observations and pollution emission

Since January 2013, the Ministry of Environmental Protection of China began to publicize real time monitoring data of 6 major pollutants over 74 cities, which include $PM_{2.5}$, PM_{10}, O_3, SO_2, NO_2 and CO respectively. This dataset has been used in many studies and can be obtained from http://datacenter.mep.gov.cn/ (Ma et al., 2014; Chen et al., 2015). In our study, we adopted hourly NO_2 and SO_2 mass concentrations from 2014 to 2016 in five cities of Inner Mongolia, which are provided by Inner Mongolia Municipal Environmental Protection. There are totally 31 monitoring stations, including 10 sites in Hohhut, 7 sites in Baotou, 3 sites in Ordos, 6 sites in Bayannur and 5 sites in Wuhai, which are shown in Fig. 1. These data are used for the evaluation of satellite observations and analysis of seasonal and diurnal variation of near-surface NO_2 and SO_2 concentrations.

To study the influence of the emission source on the air quality, we collected data on two aspects from the China Statistical Yearbook: one is the consumption data of various types of energy, such as coal, fuel and gas; the other is the emission data of gaseous pollutants from industrial and domestic activities, which includes NO_2, SO_2 and smoke. This data can be downloaded from http://www.stats.gov.cn/tjsj/ndsj/.

2.4. Meteorological data

The washout process of rainfall on NO_2 and SO_2 in the atmosphere can reduce the air pollution near the surface, in addition to producing acidic precipitation. To study the seasonal variation characteristics of precipitation and its potential effect on surface air pollution in Inner Mongolia, we use China Hourly Merged Precipitation Analysis (CMPA) product from 2014 to 2016. The CMPA product has merged observations from automatic weather stations with Climate Precipitation Center Morphing (CMORPH) product based on the probability density function–optimal interpolation (PDF-OI) methods, with a spatial resolution of 0.1° × 0.1°. The overall error of this dataset is within 10% and the errors for regions with heavy rainfall or sparse ground sites are less than 20% (Shen et al., 2014). The surface solar radiation downwards (SSRD) and planetary boundary layer height (PBLH) are extracted from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al., 2011), with a horizontal resolution of 0.125° × 0.125° and 3 h temporal resolution.

3. Analysis and results

3.1. Comparison between satellite and ground observations

Considering that satellite observations have much coarser temporal and spatial resolution than the ground observations, we generally need carry out the spatial-temporal matching, which figures out the spatial domain with satellite observation average more comparable to the surface measurements and the time range with the surface observation average more comparable to the satellite measurements. Spatial-temporal matching is an essential condition for the comparison between satellite and ground observations since it can reduce the errors caused by the temporal change and spatial heterogeneity of NO_2 and SO_2. As for the spatial matching, the spatial averaged OMI VCD NO_2 and SO_2 within 100, 50, 30 and 10 km radius regions surrounding the surface monitoring station as the center were compared to the ground observed values, and it shows that when the radius is 30 km, the observations from satellite have the highest consistency with those from surface stations. Therefore, we used 30 km as a critical value for the regional average of satellite observations. Note that we only tested the domains with 100, 50, 30 and 10 km radius, domain with another value radius could be more suitable while not tested. With regard to temporal matching, only when the OMI data is available, the corresponding ground-observed NO_2 and SO_2 in time within 30-min of the satellite overpass time are compared to OMI measurements. Fig. 2 shows the comparison of NO_2 and SO_2 between monthly averaged OMI VCD products scaled by planetary boundary layer height (PBLH) and the ground-based measurements using the data from 2014 to 2016 in Inner Mongolia. PBLH is likely the most important factor to the vertical distribution of NO_2 and SO_2. In general, NO_2 and SO_2, along with fine aerosol particles, mainly concentrate within PBLH. Moreover, the planetary boundary layer is a well-mixed layer in which NO_2 and SO_2 vary weakly with heights. We could consider the impacts of vertical profile on our inter-comparison roughly by using PBL scaled column NO_2 and SO_2 (VCD NO_2/PBL and VCD SO_2/PBL), making them more comparable to the ground based measurements of NO_2 and SO_2 concentration. Overall, the correlations are high, with R^2 of 0.80 for NO_2 and 0.48 for SO_2. It demonstrates that the satellite is an effective way to monitor the monthly-averaged characteristics of surface SO_2 and NO_2. However, when using daily measurements, the correlations between satellite and ground station observations for both SO_2 and NO_2 are low, which can be attributed to multiple reasons. First, the gridded OMI product represents an averaged NO_2 and SO_2 status of a region while the ground station reflects the status at a single site. Noting that anthropogenic pollutants could serve as a dominant contributing source in addition to the contribution from natural emissions (Cui et al., 2016), the spatial heterogeneity of pollutants caused by the emission difference and meteorological condition makes R^2 not very high. Second, the influence of cloud and aerosol can bring uncertainties to the OMI retrievals to some extent. In addition, the lack of more precise consideration for the vertical profile of NO_2 and SO_2 could lead to noticeable errors in the comparison between the surface concentrations and satellite-observed columns. For example, Lamsal et al. (2015) indicated up to 15% errors in the temporal trend estimation of NO_2 emission when using OMI column NO_2.

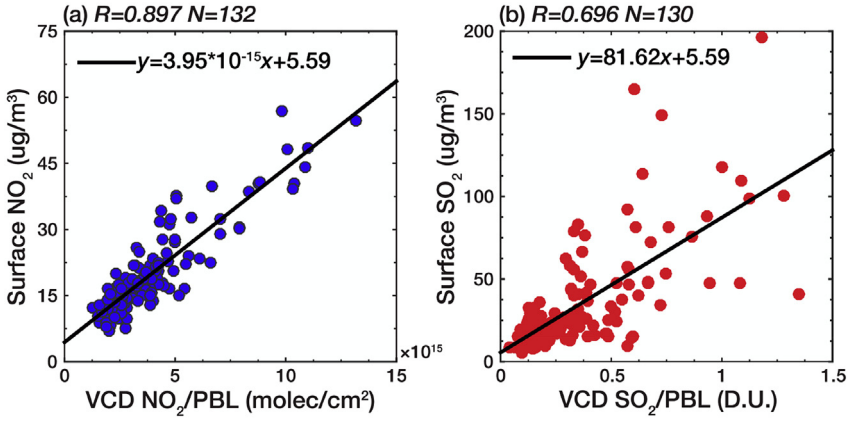

Fig. 2. The comparison between OMI VCD product and ground-based observations for NO_2 (a) and SO_2 (b).

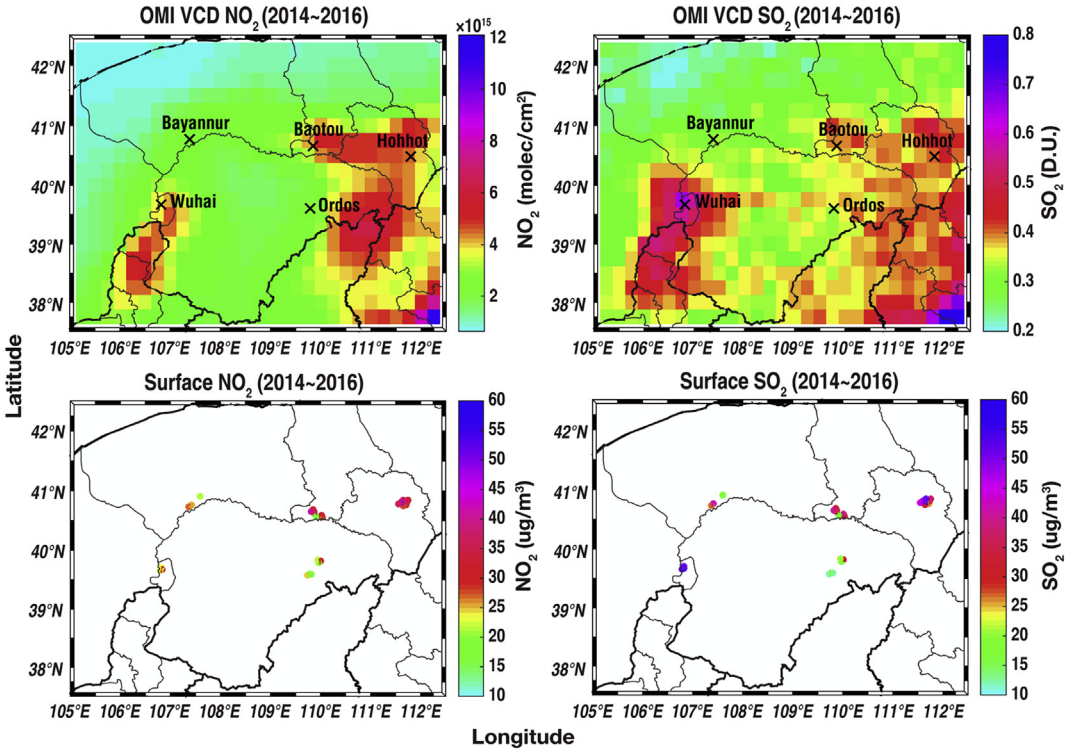

Fig. 3. Spatial distribution of averaged VCD NO_2 (a), VCD SO_2 (b), surface NO_2 (c) and surface SO_2 concentrations (d) from 2014 to 2016 in Inner Mongolia urban agglomerations.

3.2. Spatial and temporal distribution of NO_2 and SO_2

Fig. 3 describes the spatial distribution of satellite- and ground-based NO_2 and SO_2 averaged for the period from 2014 to 2016 in Inner Mongolia urban agglomerations. It shows that highly polluted areas are concentrated in the cities with industrial clusters while the suburbs are less polluted. In terms of the spatial distribution of NO_2, the highest levels of pollution occur in Hohhot and Baotou, followed by Wuhai and Ordos, the least polluted area in Bayannur. Compared with NO_2, the SO_2 spatial distribution is slightly different. The pollution of SO_2 is the most serious in Wuhai, followed by Hohhot and Baotou, and the lightest in Ordos and Bayannur. In general, Bayannur has a better air quality and the SO_2 amount in Wuhai is much larger than that in other cities, with a multi-year average value of 67 $\mu g/m^3$. It was shown that the SO_2 emission intensity per unit area of Wuhai is 33 times as much as the national average level in 2015, which is much higher than other coal-producing cities (NIW, 2017). High SO_2 pollution in Wuhai can be attributed to several factors, including unreasonable industrial layout, industrial recovery, spontaneous combustion of coal seam and special topography and climate conditions (NIW, 2017), which has attracted the attention of Wuhai municipal government for recent years. Overall, both satellite and ground observations show similar results regarding the heavily, moderately and slightly polluted regions. Fig. 3 also reveals the superiority of satellite remote sensing observations in large spatial scale analysis of air pollution.

Fig. 4 shows both monthly and seasonal variations of VCD NO_2, VCD SO_2 and rain rate from 2005 to 2016 in Inner Mongolia. The monthly averaged VCD NO_2 and SO_2 show periodic changes with one year as a cycle, reaching its maximum values in winter and minimum values in summer. The rain rate also shows a one-year periodic change. However, the seasonal variation of rain rate is opposite to that of VCD NO_2 and VCD SO_2, which may be partly due to the fact that the wet deposition of precipitation can significantly reduce the amount of pollutants in the atmosphere (Feng et al., 2001). In other words, abundant precipitation

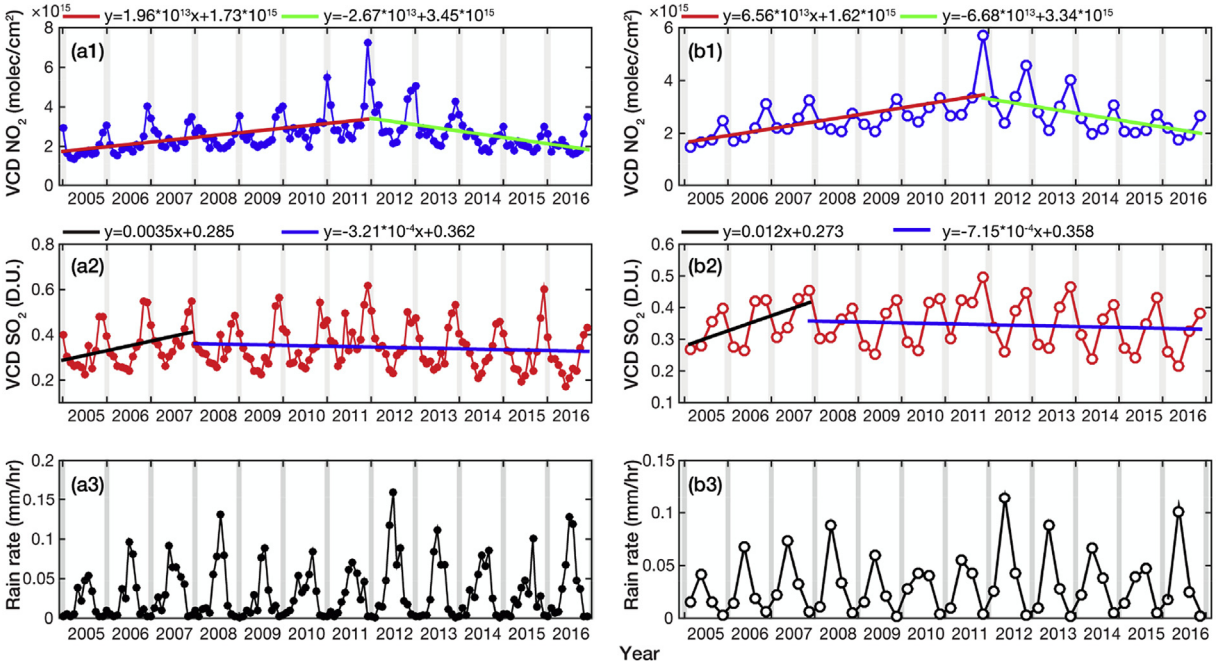

Fig. 4. Temporal variations of VCD NO_2 (the upper), VCD SO_2 (the middle) and rain rate (the lower) in Inner Mongolia. The left is the changes of monthly averaged values and the right is the seasonal variation. The lines in the figure represent the temporal trend.

caused by summer monsoon could be an important factor contributing to low NO_2 and SO_2 in summer. Another important influential factor to the seasonal variation of VCD NO_2 and SO_2 is the more serious emissions in cold winter period.

Fig. 4 also shows that there are different temporal trends for both monthly and seasonally averaged VCD NO_2 between before and after 2011. Before 2011, there is a clear increasing trend in the monthly and seasonally averaged VCD NO_2 with an increasing rate of 1.1% per month. After 2011, the trend has become decreasing with time. Differently, the monthly and seasonally averaged VCD SO_2 shows a turning change in the temporal trends in 2007 instead of 2011. The VCD SO_2 increased with time before 2007, and decreased with time after 2007. To further examine this, Fig. 5 shows the temporal variation of annually averaged VCD NO_2 and SO_2, which divides all time into two periods, one with an increasing and the other with a decreasing trend. For NO_2, it goes up from $\sim 1.7 \times 10^{15}$ in 2005 to $\sim 3.5 \times 10^{15}$ (molecules/cm^2) in 2011 with an increasing rate of $\sim$14.4% per year except a slight decline in 2008, which may be caused by pollution control and mitigation measures for the 2008 Olympic Games. However, the period of 2011–2016 witnesses a noticeable downward trend for NO_2 with a decreasing rate of $\sim$8.1% per year. In contrast, the SO_2 increases from $\sim$0.32 in 2005 to $\sim$0.37 (D.U.) in 2007 with an increasing rate of $\sim$9.7%. For the period from 2007 to 2016, it shows a general downward trend with a decreasing trend of $\sim$1.6% despite of a great upswing in 2011.

It is expected that the spatial and temporal trends of NO_2 and SO_2 should be closely associated with the energy consumption structure and exhaust emissions over the study areas. Fig. 6 shows the annual variation of the NO_2 and SO_2 emissions from China and Inner Mongolia, along with the annual variation of consumption of energy in Inner Mongolia (Table 1). Inner Mongolia has served as the energy and heavy-chemistry base of China for a long time. Coal is the main energy resource for Inner Mongolia, accounting for more than 94% of the energy consumption of the industry (NBS, 2013). The consumption of fossil fuel keeps a consistent increase with a growth rate of 14.8% for coal and 18.1% for fuel from 2005 to 2011 and then decreases from 2012 to 2015 despite of slight fluctuations. However, the emission of SO_2 shows a general declining trend due to the economic policy adjustment and technical improvement.

The 11th Five Year Plan (FYP) which was issued in 2005 requires

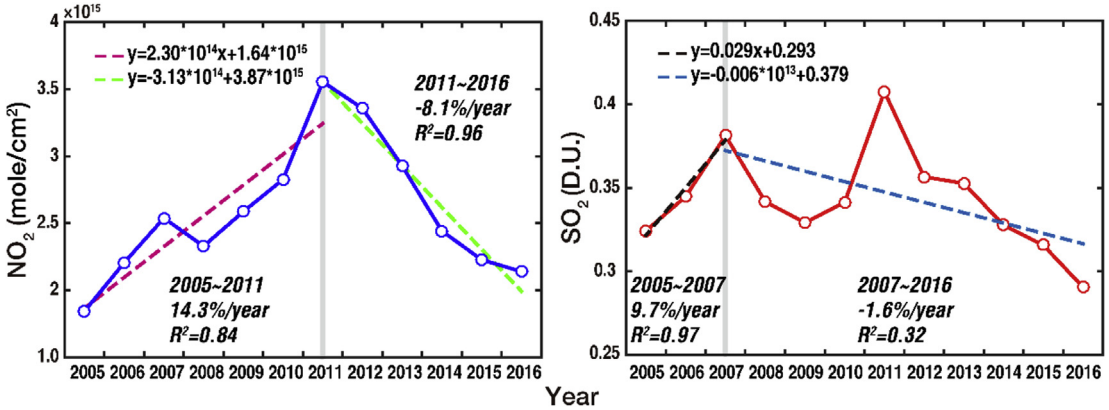

Fig. 5. Temporal variations of yearly averaged VCD NO_2 and SO_2 during the period of 2005–2016 in Inner Mongolia urban agglomerations, along with their temporal trends (dashed lines).

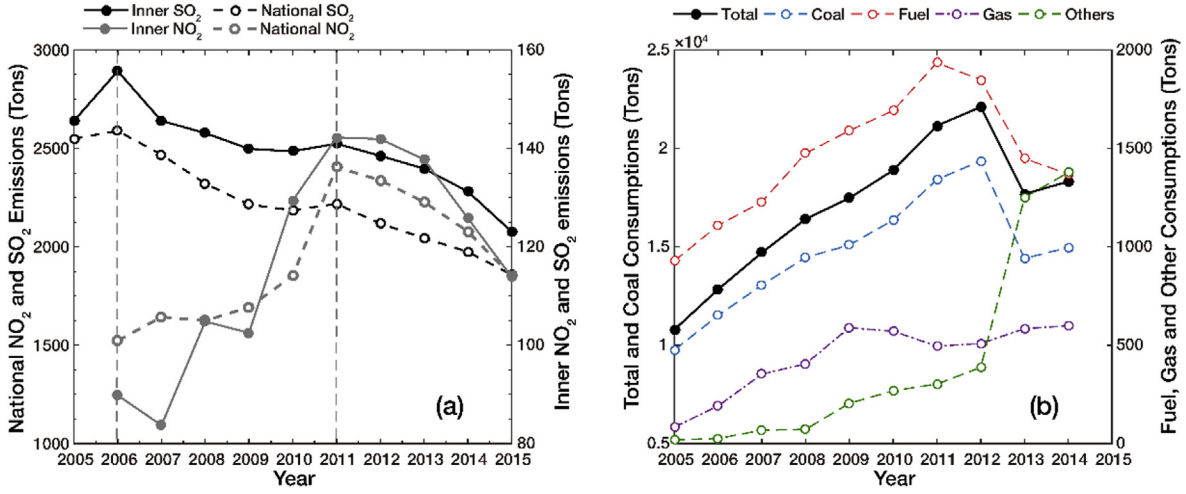

Fig. 6. Tailpipe emission of China and Inner Mongolia including NO_2 and SO_2 (a), and the energy consumption structure of Inner Mongolia (b). The energy consumption in (b) includes the total, coal, fuel, gas and others. The others here are clean energy including hydropower, nuclear power and so on.

that the emission of SO_2 decline 3.2% in 2010 according to the environmental protection goal (IMESB, 2006). To meet the goal, the traditional coal fired boilers have been modified or abandoned. Meanwhile, a lot of waste gas treatment facilities were installed to realize the flue gas desulfurization (FGD), making the SO_2 removal rate increase from 24.1% in 2006 to 57.3% in 2010. In 2007, Inner Mongolia's total SO_2 emission was about 145.59 million tons (88% from industrial activities) and ranked 4th in China. By contrast, it was reduced by 6.19 million tons in 2010. Due to the economy resurgence, a temporary recovery of SO_2 emission was done in 2011 with a growth rate of 0.86% compared with 2010, which is consistent with the trend observed in Fig. 5(b). After that, the SO_2 emission decreased continuously and reduced by 17.85 million tons in 2015.

The energy consumption keeps going up for the sake of rapid economic development in Inner Mongolia during the period from 2006 to 2015. Correspondingly, the NO_2 emission grows up strikingly from 89.82 in 2006 to 129.38 million tons in 2010, with an annual growth rate of 8.8%. One likely reason is that the removal rate of NO_x in industrial processes is generally low with a rate of 2.9%. The China 12th FYP policy is expected to realize 10% NO_x reduction compared to the 2010 level in 2015. Ambient air quality standards (GB3095-2012) was announced which require traffic, agricultural and industrial coordinated emission reduction. Moreover, more and more clean energy are being used in Inner Mongolia, such as the establishment of wind farms. The usage of alternative energy may promote the transformation and optimization of industrial structure, contributing to the improvement of urban air quality in the future. As a result, NO_2 emission decreased significantly by 28.3 million tons in 2015. As is shown in Fig. 6, the temporal changing trend of NO_2 and SO_2 emissions in China is roughly consistent with that in Inner Mongolia.

Fig. 7 further shows the spatial distributions of biennial averaged VCD NO_2 and SO_2 from 2005 to 2016 in Inner Mongolia urban agglomerations. The high polluted hotspots of VCD NO_2 are mainly centralized in areas with high population, industrialization, urbanization and agricultural activities. From 2005 to 2011, the NO_2 pollution area surrounding key cities is expanding and the pollution level is rising, which is consistent with the increase of NO_2 emission shown in Fig. 6. Nevertheless, the NO_2 pollution over the areas around the cities becomes to decrease with time from 2012. Differently, the biennial averaged VCD SO_2 increases slightly from 2005-2006 to 2007–2008, and then experiences a continuous decrease with time from 2007. This is also roughly consistent with the temporal trend of SO_2 emission amount in this region as shown in Fig. 6.

3.3. Pollution over five cities

Fig. 8 shows the monthly averaged surface NO_2 and SO_2 in five cities, and rain rate and SSRD over the Inner Mongolia. Overall, the monthly variation of NO_2 and SO_2 concentrations presents a “U” shape curve, with peaks in winter and valleys in summer. Emission source is one of the main factors leading to this seasonal variation, along with the seasonal changes of chemical lifetime of NO_2 and SO_2, planetary boundary layer height, precipitation and other meteorology variables. For the emission source, coal-fired heating emissions in winter should be an important contributing factor. In addition, it has been figured out that the lifetime of NO_x in winter is several times longer than in summer (Cui et al., 2016), and the lifetime of SO_2 in winter (58 ± 20 h) is also a few times longer than in summer (19 ± 7 h) (Lee et al., 2011). This

Table 1
Annual emission of different kinds of exhaust gases from 2005 to 2016 in Inner Mongolia (unit: tons).

	Industrial SO_2 (Tons)	Life SO_2 (Tons)	Total SO_2 (Tons)	Industrial smoke (Tons)	Life smoke (Tons)	Industrial dust (Tons)	Total smoke and dust (Tons)	NOx (Tons)
2005	129.60	16.00	145.60	60.40	17.50	45.60	123.50	–
2006	138.40	17.30	155.70	48.80	17.20	27.00	93.00	89.82
2007	128.33	17.26	145.58	50.40	16.01	20.04	86.45	83.70
2008	125.86	17.25	143.11	42.84	15.05	20.96	78.84	104.77
2009	120.40	19.48	139.88	32.05	17.32	16.41	65.79	102.48
2010	119.30	20.11	139.41	47.59	17.10	16.04	80.73	129.38
2011	**125.02**	15.92	140.94	–	–	–	73.99	142.20
2012	124.15	14.34	138.49	–	–	–	83.30	141.89
2013	123.64	12.23	135.87	–	–	–	82.21	137.76
2014	116.71	14.53	131.24	–	–	–	102.15	125.83
2015	106.10	16.99	123.09	–	–	–	87.88	113.90

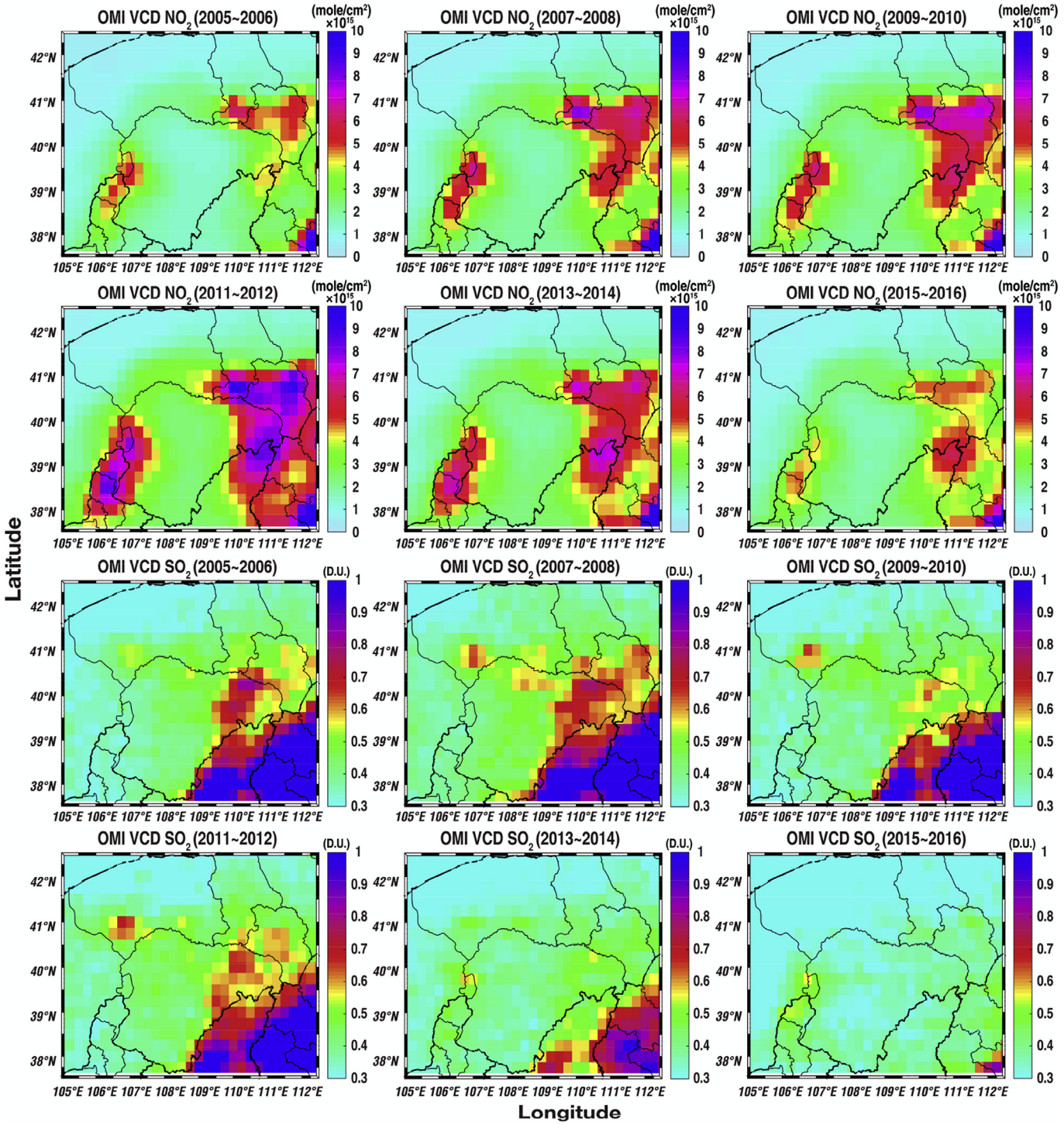

Fig. 7. Spatial distributions of biennial averaged VCD NO_2 and SO_2 from 2005 to 2016 in Inner Mongolia urban agglomerations.

seasonal variation of lifetime will contribute to higher NO_2 and SO_2 concentration in winter than in summer. Fig. 8(c–d) demonstrate that both rain days and SSRD show an opposite monthly variation compared to that of NO_2 and SO_2. In summer, the wet scavenging of precipitation can significantly reduce the concentration of atmospheric pollutants. Also, the high temperature and relative humidity in summer atmosphere are beneficial to the removal of NO_2 through photolysis (Feng et al., 2001; Dong et al., 2009). By contrast, in winter, radiation reaching on the ground is less and the boundary layer decreases a lot, causing the build-up of near surface air pollutants and thus more serious air pollution.

Fig. 9 shows the diurnal variation of surface NO_2 and SO_2 concentrations at five cities in Inner Mongolia for the period from 2014 to 2016. In general, the SO_2 shows a bimodal pattern with a flat "W" shape for the diurnal cycle in all five cities except for Wuhai. For most cities other than Wuhai, the lowest SO_2 concentration appears at around 3:00–5:00 LT and 15:00–19:00 LT while the peak appears at about 8:00–11:00 LT and 20:00–24:00 LT, which is highly related to the human activities and meteorological condition. Obviously, during the period from 6:00 to 8:00 LT, anthropogenic activities start, and a combination of vehicle exhaust fumes and factory waste gases result in the growth of SO_2 concentration. However, from 9:00 to 16:00 LT, with

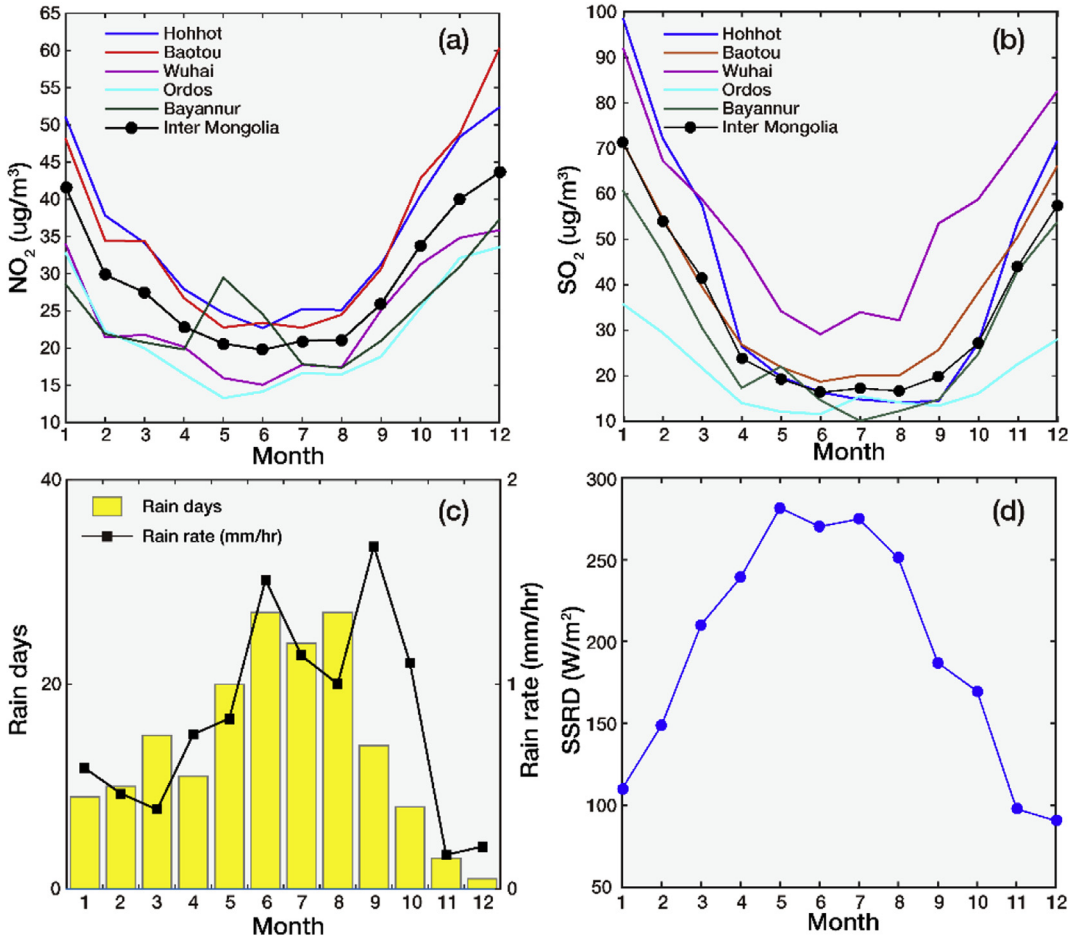

Fig. 8. Monthly averaged NO_2 (a), SO_2 (b), rain days and rain rate (c) and SSRD (d) of Inner Mongolia urban agglomerations from 2014 to 2016.

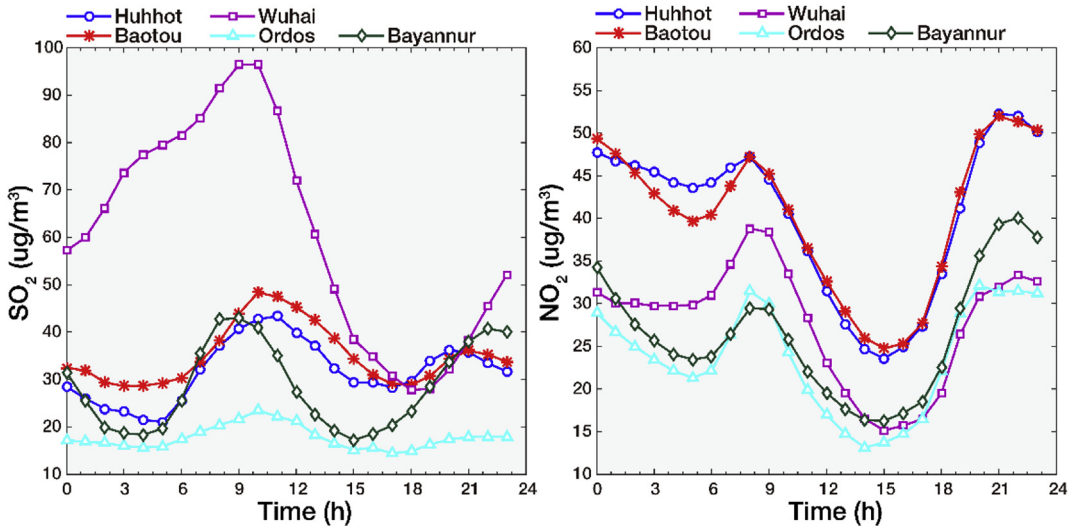

Fig. 9. Diurnal variation of surface SO_2 (a) and NO_2 (b) in five cities of Inner Mongolia during the period from 2014 to 2016.

the increase of solar radiation reaching the surface, the turbulence and exchange of pollutants in the vertical direction of atmosphere become more active, resulting in much higher boundary layer, less accumulation of near-surface pollutants, and thus lower SO_2 concentrations.

Different from other four cities, SO_2 concentration in Wuhai shows a single mode diurnal variation with maximum values around 9:00 LT and minimum values around 18:00 LT. Moreover, Wuhai suffers more SO_2 with a peak value reaching 100 μg/m^3. This could be associated with its industrial structure and urban layout. Heavy industry for power and heat generation, petroleum processing, coke making, and so on, produces serious SO_2 emissions. Meanwhile, the industrial zone is mainly distributed in the south area of Wuhai which is on the upwind direction of the urban district for most time (Chen and Bai, 2014).

The diurnal variation of NO_2 shows the similar bimodal distribution as that for SO_2. Differently, NO_2 over all five cities shows the maximum values around 8:00–9:00 LT and 19:00–22:00 LT, and the minimum

values around 5:00 LT and 15:00 LT. From 9:00 to 15:00 LT, associated with the increase of solar radiation, the boundary layer height rises and the photochemical reaction process of NO_2 and volatile organic compounds (VOC) to O_3 increases, resulting in the decreasing trend of NO_2 concentrations (Duncan et al., 2010). The night time decrease of NO_2 from 22:00 to 5:00 LT could be related to the reduced anthropogenic activities (e.g., vehicles) during this period. It's worth noting that the air quality of Ordos is relatively better than that of other cities with SO_2 and NO_2 both lower than 30 $\mu g/m^3$.

4. Summary

Combing NO_2 and SO_2 column density product derived from OMI satellite with the surface concentrations from ground station observations, this study analyzed the spatial-temporal distribution characteristics of NO_2 and SO_2 in the Inner Mongolia urban agglomeration. While there are numerous studies about the spatio-temporal variation of NO_2 and/or SO_2 in China based on OMI satellite observations, this study provides unique information for both NO_2 and SO_2 from 2005 to 2016 at a city scale over Inner Mongolia.

In terms of long-term changing trend, NO_2 increased continually from 2005 to 2011 at a rate of 14.3% per year and then decreased from 2011 to 2016 at a rate of 8.1% per year. Differently, there is a consistent increase for SO_2 from 2005 to 2007 at a rate of 9.7% per year. During the period from 2007 to 2016, despite of a peak value in 2011, it showed a decreasing trend for SO_2 at a rate of 1.6% per year.

As for the spatial pattern of NO_2, the highest levels of pollution occur in Hohhot and Baotou, followed by Wuhai and Ordos, the least polluted area in Bayannur. Compared with NO_2, the SO_2 spatial distribution is slightly different. The pollution of SO_2 is the most serious in Wuhai, followed by Hohhot and Baotou, and it is the lightest in Ordos and Bayannur.

The diurnal variation of NO_2 and SO_2 is basically the same, which shows bimodal pattern with a flat "W" shape, particularly for cities other than Wuhai. This type of diurnal variation of NO_2 and SO_2 is highly related to the diurnal variation of anthropogenic emission and boundary layer height. The long-term spatial-temporal distributions of NO_2 and SO_2 are closely related to human activities, while meteorology also plays an important role for their diurnal and seasonal variations.

Overall, the adjustment of the urban energy structure, such as the reduction of fossil energy use and the promotion of clean energy development, and the installment of waste gas treatment facilities contribute to the decrease of NO_2 and SO_2 emissions in recent years. Therefore, the air quality in Inner Mongolia has generally improved over the past few years. However, the turning year from increasing trend to decreasing trend is different for NO_2 and SO_2. Moreover, the SO_2 pollution situation in Wuhai is still very serious and additional efforts should be made to fully control and govern air pollution caused by human activities.

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